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ON 1/29/74 BY D. Starkweather

RESEARCH MEMORANDUM

A PRELIMINARY FLIGHT INVESTIGATION OF

AN OIL-FLOW TECHNIQUE FOR AIR-FLOW VISUALIZATION

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
October 27, 1954

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SUMMARY

A preliminary flight investigation was made to evaluate an oil-flow technique for air-flow visualization. Mixtures of silicone oil and finely powdered graphite particles were spread on the outer wing panel of a swept-wing jet-powered airplane. Results are presented in the form of photographs of the oil patterns taken in flight at transonic speeds and on the ground immediately following flight at high speeds. Also included for general interest and comparison purposes are several shadowgraph pictures and one tuft picture.

Although the interpretation of oil-flow-pattern pictures is still in its infancy, the method appears promising for flight research work because the oil-graphite film is shown to be capable of indicating shock-wave locations, separated areas, transition fronts, aerodynamically bad excrescences, flow leaks through gaps, and other significant phenomena. The method appears especially attractive for drag-clean-up work on new airplanes because of its extreme simplicity. The success of the oil-flow technique apears to depend heavily on the choice of oil viscosity. Silicone oils having viscosities ranging from roughly 10,000 to 20,000 centistokes at 25° C appear most suitable for flow-visualization work on present-day transonic airplanes.

INTRODUCTION

The importance of flow-visualization techniques in leading to solutions of many complex aerodynamic-flow problems, especially those involving separated- or nonpotential-flow phenomena, need hardly be emphasized. Up to the present time, nearly all attempts to visualize air flow in full-scale flight tests have been made with tufts, although chemical methods, which reveal boundary-layer-transition fronts, have been employed in a few cases (notably in England).

Kerosene-lampblack mixtures coated on an entire wing surface, or "ink" exuded from small orifices in a wing surface have assumed importance recently as flow-visualization schemes in wind tunnels. Variations of these two techniques show considerable promise for application to full-scale flight testing in view of the introduction of silicone-base oils which do not freeze at the very low temperatures encountered in flight at extreme altitudes.

The purpose of this paper is to present some photographs obtained from a preliminary flight investigation in which mixtures of fine graphite particles and silicone oils of high viscosity were spread on the outer wing panel of a jet airplane which had a 35° sweptback wing.

Although the primary purpose of these preliminary tests was to determine what oil patterns could reveal, fortuitous conditions existing during one dive resulted in obtaining a series of shadowgraph pictures of shock waves moving back on the wing. Some of these pictures are included, both for comparison purposes and for their intrinsic interest in connection with flow visualization. Also, one tuft picture from unpublished flight data is included for comparison purposes.

APPARATUS AND PROCEDURE

The preparatory procedure consisted of mixing thoroughly 2 gallons of clear silicone-base oil with 2 pounds of finely powdered graphite. This mixture was then spread evenly over approximately the outer two-thirds of the left-wing-panel upper surface of a North American F-86A airplane. The airplane was then flown as soon as was convenient. During flight, 16-mm motion pictures were taken with two cameras mounted, as shown in figure 1, in the fuselage and canopy of the airplane. Immediately after landing, a number of still pictures were taken of various patterns considered to be of interest which still persisted in the oil film.

The flight program consisted in making relatively low-speed steady climbs to 43,000 feet altitude preparatory to the test runs. The test runs consisted of high-speed dives from 43,000 to 30,000 feet altitude followed by 2g pull-outs. During these runs, the maximum Mach numbers attained ranged from approximately 0.96 to 1.05. After two of these dives in each flight, normal let-down, approach, and landing procedures were followed.

The various silicone oils used in these preliminary tests had viscosity ratings ranging from 7,500 to 20,000 centistokes at 25° C which is the standard temperature used for quoting such viscosity ratings.

RESULTS AND DISCUSSION

Enlarged photographs of separate frames of the 16-mm motion pictures of the left wing panel taken from the fuselage and canopy of the F-86A airplane are shown in figures 2 to 5. Still pictures of the oil patterns remaining after the airplane had landed are shown in figures 6 to 11. None of the pictures shown herein have been retouched. Where necessary, sketches are given next to the photographs to draw attention to the particular phenomena of interest shown by the adjacent photograph.

Flight pictures.- Figure 2 is a closeup of the rear portion of the left wing panel taken by the fuselage camera while the airplane was in level flight immediately prior to a dive. A silicone oil with a viscosity of 17,500 centistokes was on the wing and the sun was directly ahead of the airplane at about 30° elevation. The main feature brought out here is that the oil, at low airspeeds, forms waves with crests perpendicular to the air-flow direction. In this picture the waves are just becoming large enough to sparkle from the reflection of sunlight off some of the crests. There is little or no flow separation indicated at this low airspeed condition. At still lower airspeeds the oil does not sparkle at all and the waves are less evident. This condition suggests that the behavior of the oil on the rearward portion of a wing surface is not unlike the behavior of the surface of a body of water with winds of varying intensity blowing over it.

Figure 3 is from the same run as figure 2 except that the airplane is in the dive at a Mach number of 0.91. In this picture the oil shows evidence of the location of the main wing shock wave crossing the wing just ahead of the inboard leading-edge corner of the aileron. At this stage and for succeeding stages of the dive, the sun was roughly perpendicular to the wing surface. The sparkling of the oil is most intense at the intersection of the shock wave with the wing surface, and the oil on areas of the wing ahead of the shock wave and on the landing flap behind the shock wave is assuming a frosty appearance, presumably because the increase in airspeed has broken down the large waves into turbulent froth in the regions of unseparated flow. The dark areas over parts of the aileron are presumed to be indications of separated flow. These characteristics are shown more distinctly in figure 4. The irregular patch of sparkling oil at the inboard end of the aileron was observed to be caused by violent flow leakage through the chordwise gap at the end of the aileron. This feature was largely independent of speed. As a matter of interest, figure 3 represents the flow conditions

for which an abrupt left wing drop is imminent on the North American F-86A airplane. This wing drop requires approximately 5° down aileron on the left wing to maintain lateral balance. Further information on the wing drop of the F-86A airplane is given in reference 1. In this connection it is regrettable that pictures similar to figure 3 were not obtained simultaneously for the right-wing panel; if this had been done, more light might have been shed on the detailed flow phenomena associated with wing drop.

Figure 4 presents a comparison of the oil-flow, tuft, and shadow-graph techniques at a Mach number of approximately 0.96. Figure 4(a) is from the same dive as figures 2 and 3 and was taken when the Mach number had reached its maximum value of 0.96. The wing shock wave has moved back onto the aileron and apparently causes flow separation over most of the outboard portion of the wing lying behind the shock wave because the oil film in this region was not sufficiently disturbed to produce any sparkling. The frosty appearance of the oil in regions of unseparated flow ahead of the shock wave and also on the landing flap behind the shock wave is very pronounced. In figure 4(a), the inboard portion of the shock wave is essentially coincident with the flap gap so that it is difficult to say with certainty which feature makes the bigger impression.

Figure 4(b) shows the tuft photograph from unpublished flight data which is included for purposes of comparison with figure 4(a). In spite of a dearth of tufts available for study, some of the essential features indicated by figure 4(a) are seen to be duplicated. Whereas the tufts give some information on the magnitude of the outflow near the flap trailing edge, the oil seems to give a much more detailed picture of the areas of separation on the aileron and the location of the shock wave.

Figure 4(c) is one of the shadowgraph pictures shown for comparison with figure 4(a). On the flight in which 4(c) was obtained, the pilot inadvertently chose a dive direction that was favorable to the production of shadow lines caused by refraction of the sun's rays passing edgewise through the shock waves at the points of tangency of the light rays and the shock waves. Although there was oil on the wing for this flight, the oil had a viscosity rating of only 10,000 centistokes. The absence of a clearly discernible imprint of the shock wave in the oil film is therefore believed to be the result of insufficient oil remaining on the wing; that is, most of the oil had already been blown off the wing.

An examination of the wing-shock shadow line in figure 4(c) and similar shadowgraph pictures and comparison with figures 4(a) and 4(b) lead to the conclusion that the shadowgraph method is an unreliable method of indicating the location of the shock-wave—wing-surface inter-section. This conclusion might, of course, be suggested by consideration

of the manner in which shadow lines are produced; that is, a dark line seen by the observer represents the absence of a sheet of light beams that have been bent by passing through part of a curved shock wave at some distance above the wing surface rather than being the result of phenomena occurring at the wing surface itself. Another drawback to the use of shadowgraphs for routine shock-wave visualization is the fact that experience indicates they cannot always be produced at will.

The foregoing discussion and pictures show conclusively that the oil-flow technique has considerable value as a means of studying shock-wave movements and growths of areas of separation on surfaces in full-scale flight investigations. This conclusion in no way detracts from the value of tufts inasmuch as tufts obviously give a detailed picture of separated flow areas if enough tufts are used and if they can be made to stay on the surface. Tufts do not, however, necessarily indicate the position of shock lines, particularly if the shock does not cause flow separation. Shadowgraphs are seen to provide interesting information concerning the overall shock patterns existing about an airplane but definite conclusions drawn from them must be viewed with caution.

Discussion of figure 5.- Although oil-flow pictures were not obtained at speeds greater than M = 0.96, shadowgraph pictures were obtained up to M = 1.05 and results from these pictures are presented and discussed below for general interest and correlation with recent wind-tunnel findings in the field of flow visualization.

In addition to the shadow of the main wing shock shown in figure 4(c), the shadow of another shock wave which is believed to form originally near the wing-root—trailing-edge—fuselage juncture and labeled "wing-root normal shock"[1] can be seen faintly. As the speed increases further, this shadow line grows immensely in prominence and is shown just before it crosses the wing tip in figure 5. Here, another unidentified shock-shadow labeled "auxiliary normal shock" appears ahead of the main normal-shock shadow. This shock may be associated with presence of the canopy on the fuselage. In a schlieren study of such shock waves made in a wind tunnel (ref. 2), the appearance and movement of the wing-root normal shock can be seen in great detail; however, the auxiliary normal shock is unaccounted for and this is believed to be explained by the absence of a canopy on the wind-tunnel model.

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[1]This shock wave is sometimes called the "deceleration-flow shock wave" because it is associated with slowing of the flow about the entire airplane. This shock wave is oriented approximately in a plane perpendicular to the direction of motion of the airplane and extends in all directions about the airplane.

In figure 5 the shadow of the main wing shock wave has moved back and becomes more nearly parallel to the trailing edge. With further increase in speed, both normal-shock-wave shadows moved rearward off the wing and the main wing shock shadow became coincident with the wing trailing edge slightly before the maximum Mach number of 1.05 had been reached.

Ground pictures.- In this preliminary evaluation of the oil-flow technique, the object was to determine how many and what kinds of phenomena could be revealed by use of oil rather than to pinpoint the particular flow pattern associated with a particular flight condition. In considering the photographs to follow, therefore, it should be remembered that the oil patterns persisting after the airplane had landed represent the integrated effect on the oil of all the flight conditions encountered by the airplane. Obviously, the flow pattern corresponding to a given flight condition could be obtained by flying the airplane in that flight condition for a reasonable period of time and then photographing the pattern either by means of suitably placed cameras in the test airplane or by employing a separate photographic airplane flying in formation with the test vehicle immediately after the pattern has been obtained. The foregoing remarks apply particularly to the determination of transition fronts near the leading edge of a wing; in the present investigation, no attempts were made to photograph the leading-edge region in flight.

Figure 6 is an overall view of the left wing panel taken approximately 15 minutes after the airplane had landed. The oil used on the wing had a viscosity rating of 10,000 centistokes and the slats were used in the normal manner; that is, the slats were unlocked in the landing condition and extended automatically during the landing.

First, it is seen that the oil reveals a number of boundary-layer transition fronts which are fairly clearly defined. The mechanism by which these fronts are formed is believed to be as follows: At the leading edge of the wing, the boundary layer is laminar and very thin so that the oil tends to be driven back by the scrubbing action of the high-velocity air flow close to the wing surface and the surface therefore appears clean. As the laminar layer thickens with rearward movement on the wing, the velocity close to the wing surface within the boundary layer decreases and the thickness and darkness of the oil therefore gradually increases. When transition to a turbulent boundary layer occurs, there is a sudden abrupt increase in the scrubbing action of the turbulent air on the oil film and a consequent abrupt change in shading from dark to light. With still further rearward chordwise movement, the turbulent boundary layer gradually thickens and causes the oil shading to become darker gradually as the velocity near the surface again gradually decreases, this time within the turbulent boundary layer.

The second interesting feature shown by the oil pattern is the turbulence wedges on the outer two sections of the slat. These wedges are always a prominent feature brought out by "china clay" or other chemical methods of visualizing boundary-layer flow. They invariably point out the locations of particularly bad rivet or screw heads or other surface excrescences such as flecks of dirt or paint.

The third interesting feature shown in figure 6 is the sharp black line of oil a few inches back from the leading edge on the outer two slat sections only. This line is believed to be evidence of a "short" leading-edge-separation bubble. Reference 3 contains a fairly complete discussion of separation bubbles and speculates that these bubbles could be expected to occur first near the tips of sweptback wings. As is fairly well known, the induced-flow effects on a sweptback wing are such as to depress and move rearward the peak negative suction pressures near the root and to magnify and move forward the peak negative suction pressures near the tip. The latter effect is conducive to the formation of short separation bubbles.

The final noteworthy feature shown by figure 6 is the evidences of rough flow at the chordwise and spanwise slat-section junctures. This rough flow must lead to increased wing drag at high speeds and to the possibility of early compressible-flow breakdown at high lift coefficients with slats locked closed.

Figure 7 is a close-up view of the outboard-wing leading edge showing a portion of the oil line thought to mark the short separation bubble and three well-defined turbulence wedges. The turbulence wedge in the center of the picture was caused by a small nick in the leading-edge skin whereas the two wedges on the right side of the picture were clearly caused by two poorly faired rivet heads. These defects in the surface could have been corrected with a file in a matter of minutes. The possibility is therefore suggested that it may be economically feasible to employ the oil-flow technique to production airplanes in order to gain increased performance at the expense of very little additional hand labor. In modern airplanes, only a few of the many faired rivet heads are bad enough to cause premature boundary-layer transition; these few offenders can apparently be located very simply and cheaply by the oil-flow technique.

Figure 8 is a close-up view of the leading edge of an inboard slat showing the detailed oil pattern formed by a slat-track adjustment screw. The top of the screw was actually below the top of the hole in the wing skin but the oil pattern behind it is similar to that found behind post-type excrescences (see, for example, ref. 4). Also shown in the lower half of the picture are small streaks in the oil arising from various surface irregularities that were too small to produce permanent transition (transition wedges).

Figure 9 is a detail view of the oil pattern at one of the slat-section chordwise junctures. Examination of the microscopic streaks in the oil film suggests that these streaks were formed by a vortex emanating from the discontinuity in the leading edge.

Consideration is now given to the oil patterns remaining on the trailing-edge portion of the wing. Figure 10 shows a general view of the wave formations that persisted after a flight with oil with a viscosity of 10,000 centistokes. Very little is yet known regarding the interpretation of these wave formations. The fact that the wave lengths increase toward the trailing edge suggests that the wave lengths must be related to such factors as boundary-layer thickness and pressure distribution over the wing. The fact that the wave crest lines are not straight might easily be interpreted to mean that free vortices existed above the wing surface (ref. 3); however, this conclusion may be premature in the absence of supporting evidence. Figure 11 is a more detailed view of wave formations remaining on the center of the aileron after a flight using heavier oil (viscosity of 17,500 centistokes) and with the slats locked closed and sealed. These patterns have a different character than those of figure 10 and can be seen much more clearly. The differences in crest-line direction at a given point on both pictures is thought to be the result of the difference in slat configuration inasmuch as both patterns are believed to have been formed mainly during the approach and landing. These wave formations were discernible for at least one hour after landing.

CONCLUDING REMARKS

Preliminary investigation of the possible value of an oil-flow technique for visualizing air flow over surfaces of aircraft in flight leads to the conclusion that this method shows considerable promise for flight test work, particularly for transonic and supersonic aircraft. Although very much remains to be learned about the interpretation of oil patterns resulting from adjacent air flow, there is little doubt that in its present form the oil-flow technique is capable of showing shock-wave locations, separated areas, transition fronts, aerodynamically bad excrescences, flow leaks through gaps, and other significant phenomena. The method appears especially attractive for drag-clean-up work on proto-type airplanes, and possibly even on production airplanes, because of extreme simplicity.

The limited work described indicates the choice of viscosity of the oil has much to do with the success of the technique. Generally speaking, lower viscosity oils appear best for the study of boundary-layer-transition phenomena whereas higher viscosity oils appear best for the study of shock wave and separation phenomena. When the silicone-oil—graphite
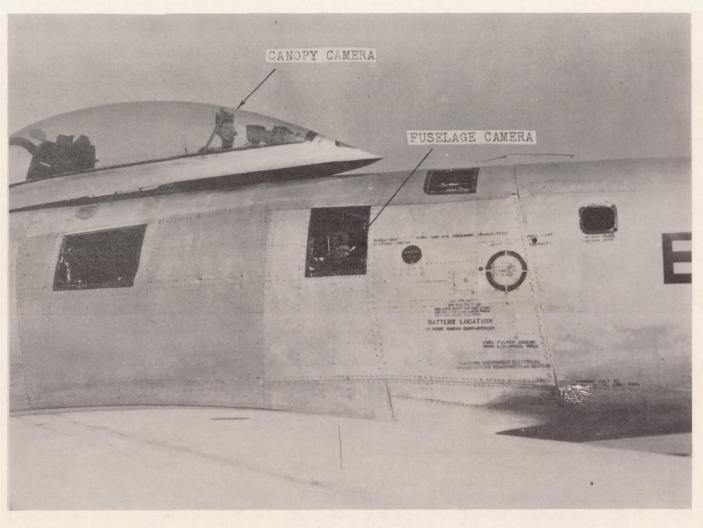
mixtures are applied on the ground, the useful range of oil viscosities appears to lie in the neighborhood of 10,000 to 20,000 centistokes (25° C) for present-day transonic airplanes.

Langley Aeronautical Laboratory,
    National Advisory Committee for Aeronautics,
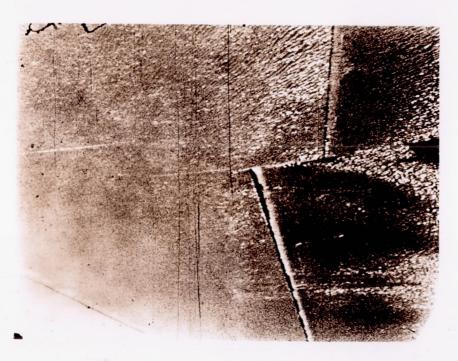   Langley Field, Va., June 29, 1954.

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2. Whitcomb, Richard T., and Kelly, Thomas C.: A Study of the Flow Over a 45° Sweptback Wing-Fuselage Combination at Transonic Mach Numbers. NACA RM L52D01, 1952.

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4. Gregory, N., and Walker, W. S.: The Effect on Transition of Isolated Surface Excrescences in the Boundary Layer. Rep. No. 13,436, British A.R.C., Oct. 12, 1950.
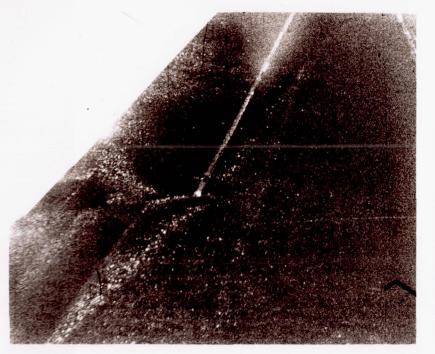
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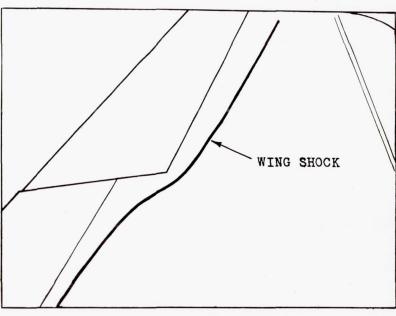
Figure 1.- Location of 16-mm motion-picture cameras in North American
F-86A airplane. Canopy camera immediately behind ejection seat with
canopy closed.

L-84914

Figure 2.- Close-up view of wave formation in oil on North American
F-86A wing. Airplane in level flight at an altitude of 43,700 feet.
Mach number, 0.85.
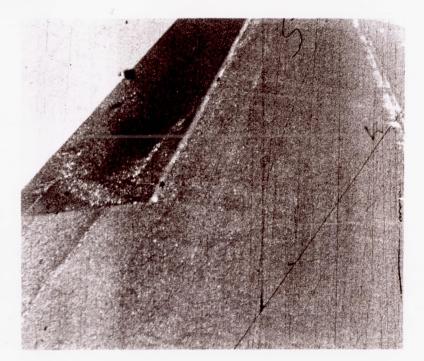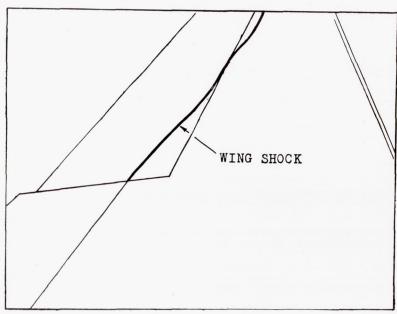
L-84915

Figure 3.- Canopy camera view of North American F-86A wing showing
imprint of wing shock wave ahead of aileron at a Mach number of
approximately 0.91. Altitude, 41,000 feet.

WING SHOCK
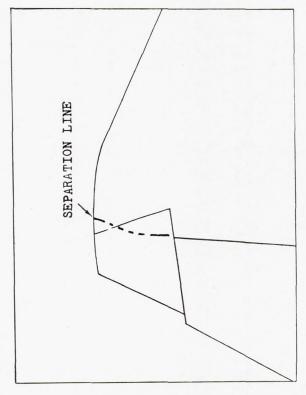
L-84916

(a) Oil-flow technique.

Figure 4.- Comparison of flow-visualization techniques on North American
F-86A wing at a Mach number of approximately 0.96.

SEPARATION LINE

L-84917

(b) Tuft technique.
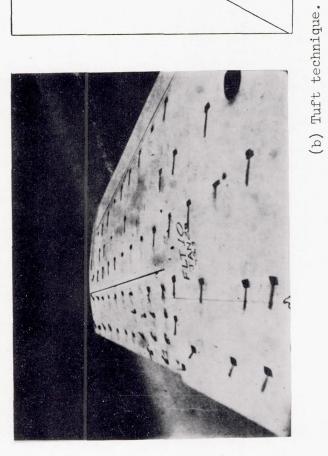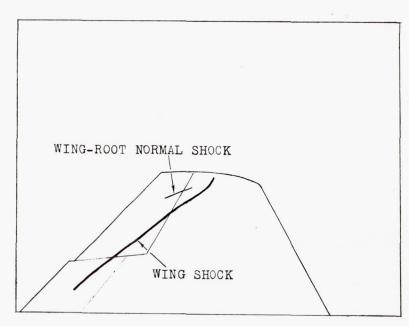
Figure 4.- Continued.

WING-ROOT NORMAL SHOCK

WING SHOCK

(c) Shadowgraph technique.   L-84918

Figure 4.- Concluded.

L-84919
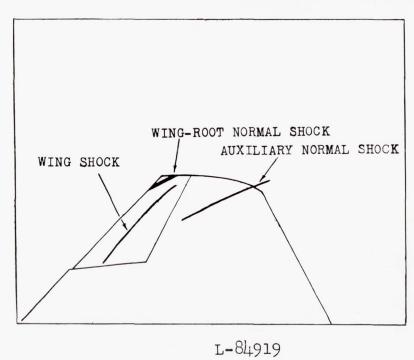
Figure 5.- Shadowgraph picture of North American F-86A wing at a Mach number of approximately 0.99.
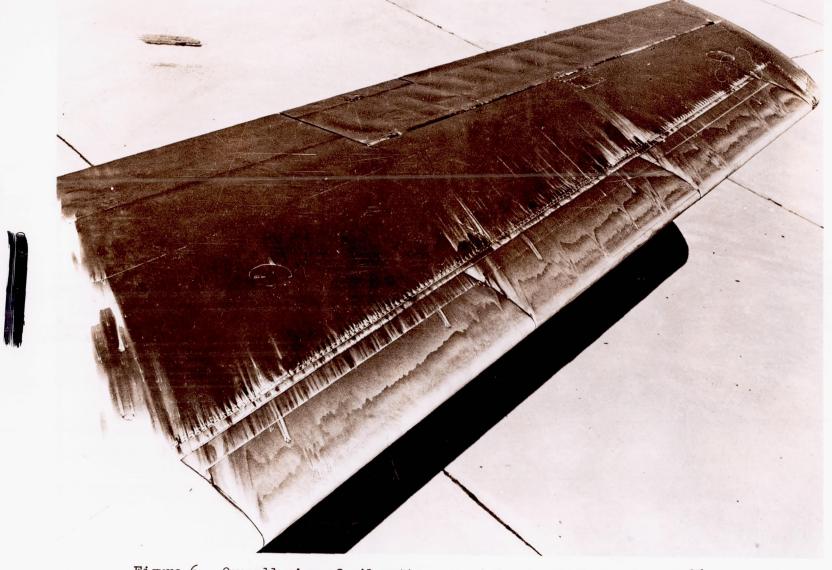
Figure 6.- Overall view of oil pattern remaining on North American F-86A wing after flight with silicone oil of 10,000 centistokes viscosity.

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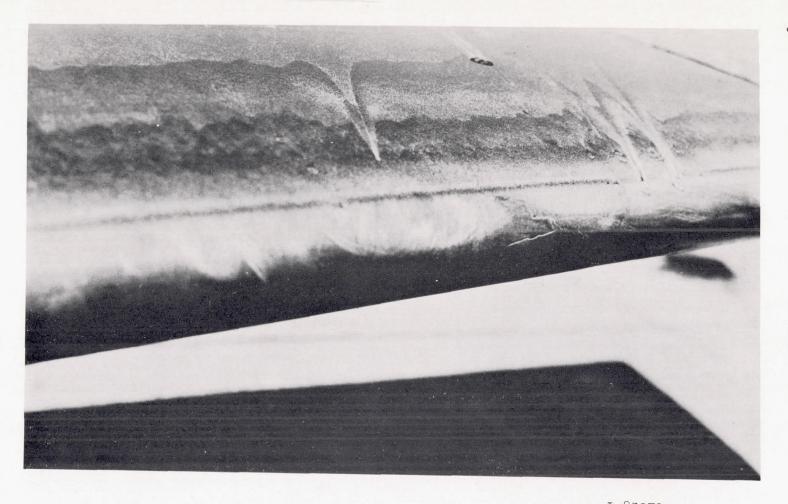
Figure 7.- Close-up view of oil pattern on leading edge of outboard slat
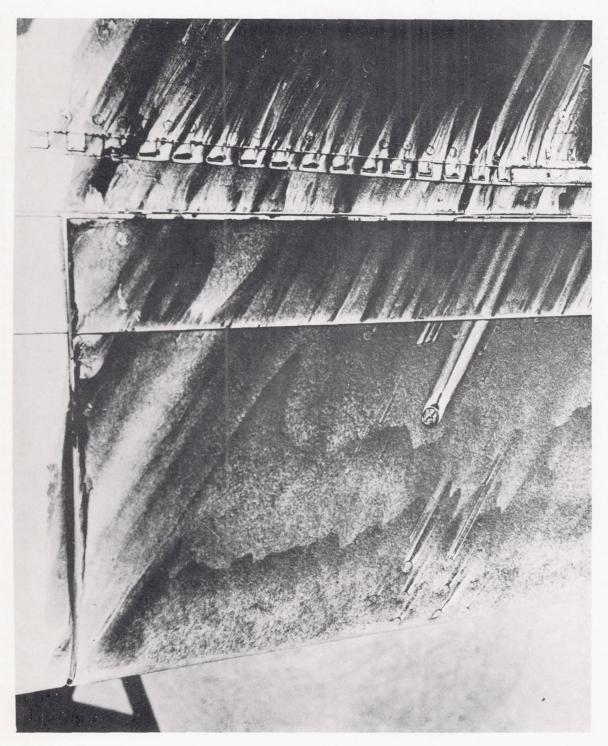section on F-86A airplane.

Figure 8.- Close-up view of oil pattern on leading edge of inboard slat section on F-86A wing.

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Figure 9.- Close-up view of oil pattern formed at slat-section juncture on North American F-86A wing.
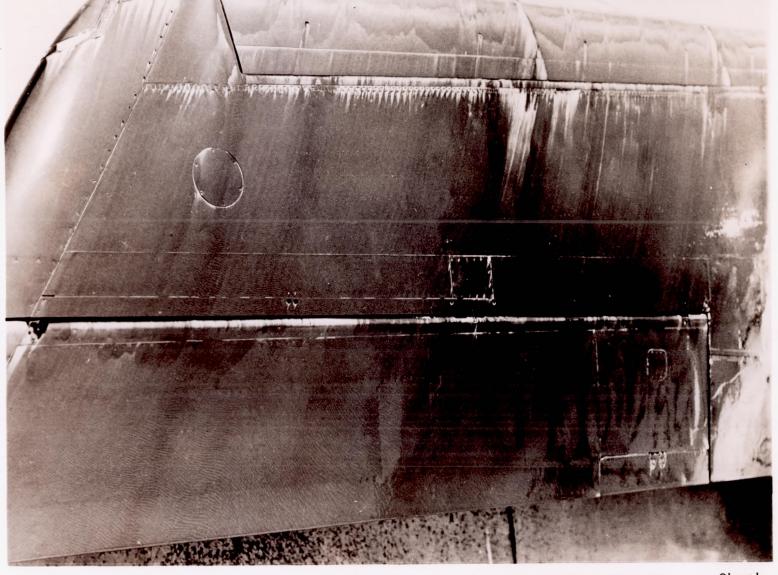
L-84923

Figure 10.- Wave formations remaining in oil film near trailing edge of
North American F-86A wing after flight with operable slats and with
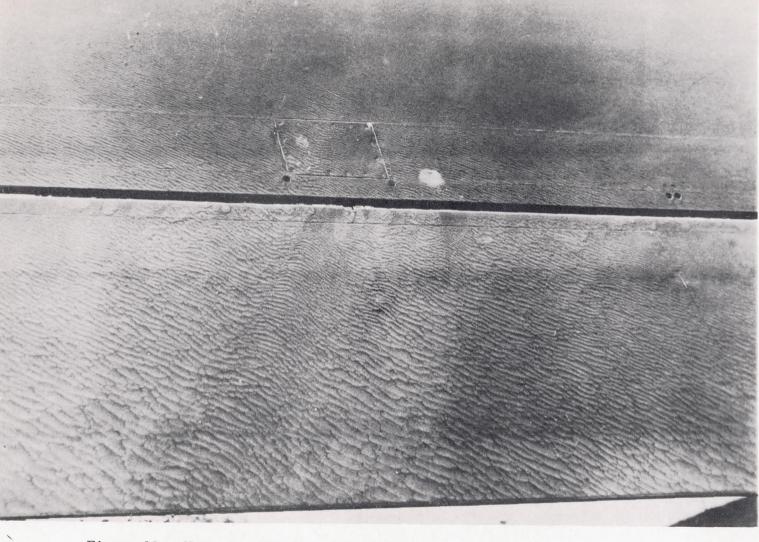silicone oil of 10,000 centistokes.

L-84924

Figure 11.- Wave formations remaining in oil film near trailing edge of North American F-86A wing after flight with slats locked closed and sealed and with silicone oil of 17,500 centistokes.

L-84925